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Recent extension driven by mantle upwelling beneath the Admiralty Mountains (East Antarctica)

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[1] Northern Victoria Land is located at the boundary between an extended, presumably hot, region (West Antarctic Rift System) and the thick, possibly cold, East Antarctic craton. The style and timing of Tertiary deformation along with relationships with the magmatic activity are still unclear, and contrasting models have been proposed. We performed structural and morphotectonic analyses at the NE termination of northern Victoria Land in the Admiralty Mountains area, where the relationship between topography, tectonics, and magmatism is expected to be well pronounced. We found evidence of two subsequent episodes of faulting, occurring concurrently with the Neogene McMurdo volcanism. The first episode is associated with dextral transtension, and it is overprinted by extensional tectonics during the emplacement of large shield alkaline volcanoes. Upper mantle seismic tomography shows that the extensional regime is limited to regions overlying a low-velocity anomaly. We interpret this anomaly to be of thermal origin, and have tested the role of large-scale upwelling on lithosphere deformation in the area. The results of this integrated analysis suggest that the morphotectonic setting of the region and the magmatism is likely the result of upwelling flow at the boundary between the cold cratonic and the hot stretched province (WARS), at work until recent time in this portion of the northern Victoria Land.

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1. Introduction

[2] The Ross Sea region (namely Victoria Land and Ross Sea) is located within the Western Antarctic Rift System (WARS), one of the largest extended and stretched continental rifts worldwide [e.g., *Wörner*, 1999, and references therein]. The evolution of the rifting, as mainly reconstructed by subsidence and uplift history, is commonly considered polyphased, involving an early Cretaceous phase linked to the Gondwana breakup followed by a major Cenozoic one [e.g., *Cooper et al.*, 1997; *Behrendt et al.*, 1991; *Tessensohn and Wörner*, 1991; *Lawver and Gahagan*, 1994; *Davey and Brancolini*, 1995; *Salvini et al.*, 1997; *Behrendt*, 1999; *Cande et al.*, 2000; *Mukasa and Dalziel*, 2000; *Cande and Stock*, 2004].

[3] There are two outstanding questions concerning the kinematic and tectonic evolution of the Cenozoic tectonic episode in the WARS. First, the pattern of deformation changes abruptly moving from Victoria Land to the western Ross Sea shoulder (Figure 1a). Offshore, Oligocene-Miocene extension produced localized subsidence along N-S trending basins [e.g., *Davey and De Santis*, 2005; *Davey et al.*, 2006] and oceanic spreading in the Adare Basin [*Cande et al.*, 2000; *Cande and Stock*, 2004] (Figure 1a). Onshore, the Ross Sea margin is crosscut by a set of right-lateral NW-SE strike-slip faults that, active from the Eocene onward [*Rossetti et al.*, 2006], reactivated the Paleozoic (Ross-aged) orogenic fabric [*Wilson*, 1995; *Salvini et al.*, 1997; *Hamilton et al.*, 2001; *Rossetti et al.*, 2003; *Storti et al.*, 2001, 2007] (Figure 1a). Second, these tectonic processes are accompanied or followed by large-scale uplift of an asymmetrically tilted block, the Transantarctic Mountains (TAM) (Figure 1). This mountain belt underwent uplift and denudation episodes in the late Cretaceous and in the Eocene [*Fitzgerald and Gleadow*, 1988; *Fitzgerald*, 1992; *Balestrieri et al.*, 1994; *Lisker*, 2002; *Lisker et al.*, 2006]. Uplift has been related to various kind of crustal flexure [*Stern and ten Brink*, 1989; *van der Beek et al.*, 1994; *ten Brink et al.*, 1997; *Busetti et al.*, 1999], enhanced by isostasy related to differential erosion [*Stern et al.*, 2005], locally localized along strike-slip fault systems [*Salvini et al.*, 1997; *Stackebrandt*, 2003; *Rossetti et al.*, 2006], or related to a thermal anomaly [e.g., *ten Brink and Stern*, 1992; *ten Brink et al.*, 1997; *Behrendt*, 1999]. Alkaline Cenozoic volcanism indeed accompanied formation of the WARS [e.g., *Wörner*, 1999, and references therein]. Magmatism started at about 48 Ma in north Victoria Land [*Tonarini et al.*, 1997; *Rocchi et al.*, 2002], getting particularly abundant over the last 15 Ma (McMurdo Volcanic Province [*LeMasurier*, 1990]), with a MORB- to OIB-type (HIMU source) imprinting [*Rocholl et al.*, 1995, *Rocchi et al.*, 2002] (Figure 1).

[4] The purpose of this paper is to unravel the relationships between tectonics and magmatism in order to shed light into the recent dynamic evolution of this region. To achieve this purpose, we performed a geological-structural

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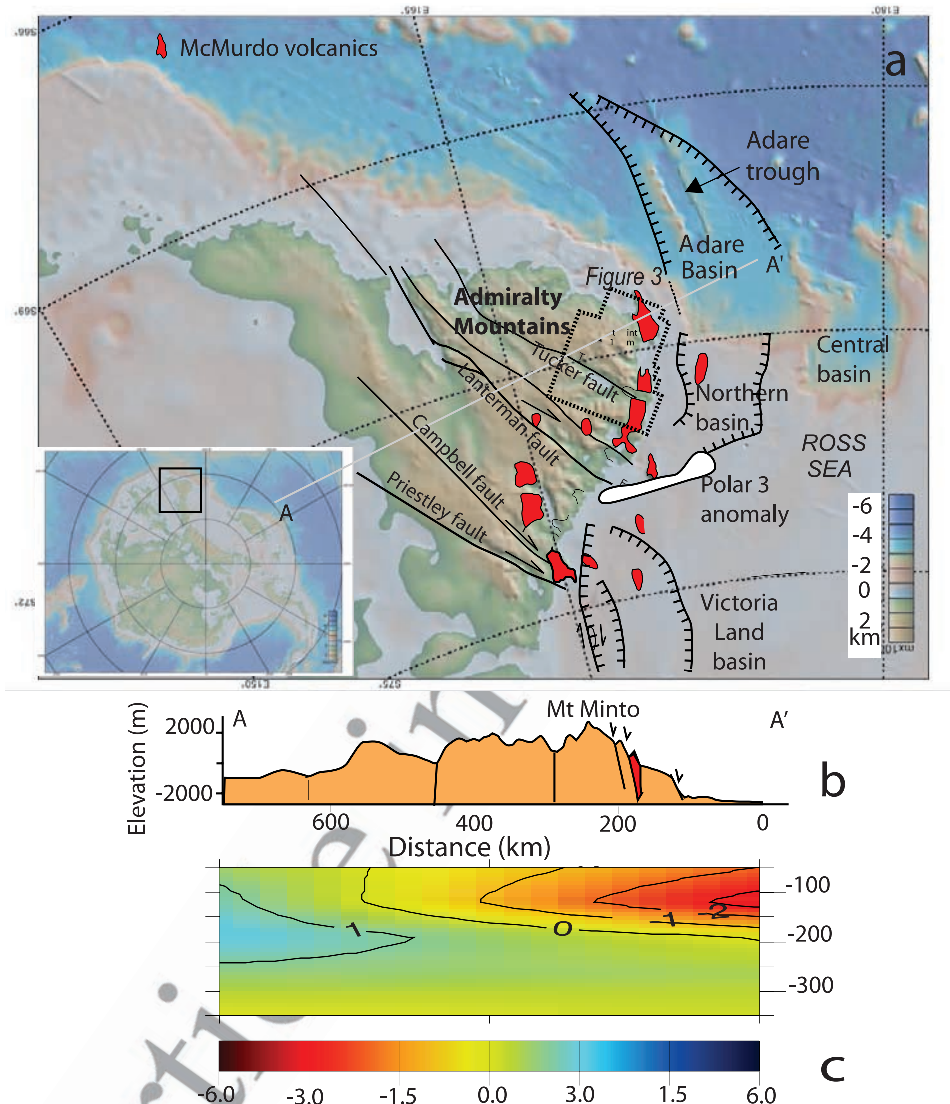


Figure 1. (a) Tectonic map of the Northern Victoria Land with main structural features and McMurdo volcanics. (b) Cross-section AA′ shows the main structure and their relationships with topography and magmatism along with (c) the corresponding upper mantle DM01 model [*Danesi and Morelli*, 2001] tomographic section (see Figure 2).

survey over the Admiralty Mountains region, positioned on the western shoulder of the Adare Basin, where uplift [*Van der Wateren et al.*, 1999; *Baroni et al.*, 2005], volcanism and tectonics [*Müller et al.*, 2005; *Läufer et al.*, 2006; *Storti et al.*, 2007] are expected to be particularly pronounced (Figure 1). We integrate our surface crustal data with the upper mantle tomographic analysis of *Danesi and Morelli* [2001] in order to investigate the possibly deep origin of the tectonic signal. We test the result of our model by comparing the shear stress reconstructed by means of field survey with the one expected from a large-scale mantle flow model driven by mantle density anomalies. This integrated analysis shows that: (1) tectonic activity persisted in the region until recent time, exerting control on the Pliocene-Pleistocene McMurdo volcanism with a continuous evolution from strike-slip to extensional faulting, probably during latest stage of TAM uplift; (2) the area of deformation is localized at the transition zone between the cold East Antarctic craton and the stretched hot continental crust of the WARS; and (3) an active mantle upwelling model is considered as the most likely explanation for the tectonic evolution of this portion of the WARS. This model reconciles the recent tectonic faulting, geomorphic evidence, volcanism, and the deep seismological structure.

2. Geological Background and the Admiralty Mountains Region

[5] The Transantarctic Mountains separate the thinned continental lithosphere of the WARS from the East Antarc-

tic craton (Figure 1). In the Northern Victoria Land, the geomorphological scenario of the TAM abruptly changes along strike crossing the Lanterman Fault, a major structural boundary separating the Neoproterozoic-Early Paleozoic Wilson Terrane from the Admiralty Block. South of the Lanterman Fault, the exhumed roots of the Early Paleozoic Ross Orogen are peneplanned below the Gondwanian terrestrial sequence, Permo-Traissic to Jurassic in age [*Lisker et al.*, 2006, and references therein]. North of the Lanterman Fault, the Admiralty Mountains landscape is characterized by an Alpine-type morphology shaped by narrow valleys and sharp cliffs with peaks reaching altitudes of more than 4000 m in the Mount Minto area [*Armienti and Baroni*, 1999; *Van der Wateren et al.*, 1999; *Baroni et al.*, 2005] (Figure 1b).

[6] The Admiralty Mountains are constituted by the Early Paleozoic volcanic rocks of the Bowers Terrane and the low-grade, turbidite-dominated deposits of Robertson Bay Terrane [*Tessensohn*, 1994]. The Robertson Bay unit consists of a thick sequence of tightly folded rock sequences, locally intruded by the Devonian-Carboniferous Admiralty intrusives [*GANOVEX Team*, 1987]. The Admiralty Mountain region is also characterized by the occurrence of distributed Cenozoic magmatism that dominantly consists of volcanic products of the McMurdo Volcanic Group [e.g., *Jordan*, 1981; *McIntosh and Kyle*, 1990; *Rocchi et al.*, 2002]. In particular, N-S elongated shield volcanoes are exposed for a distance of more than 200 km along the northern western margin of the Ross Sea, from Coulman Island to Cape Adare and the Hallet Peninsula (Hallett Volcanic Province; Figures 1a and 3). This volcanic field was active during the Middle to Late Miocene up to the Quaternary (from 14 Ma up to ~1 Ma [*Läufer et al.*, 2006, and references therein; *Mortimer et al.*, 2007].

[7] As mentioned before, the Cenozoic tectonic setting of the area is dominated by a set of regularly spaced NW-SE right-lateral strike-slip faults, such as the Lanterman Fault, that crosscut the western shoulder of the Ross Sea [*Salvini et al.*, 1997; *Rossetti et al.*, 2006; *Storti et al.*, 2007] (Figure 1). Wrench tectonics started during the Eocene (at about 40 Ma), but structural observation and offshore seismic lines indicate reworking up to recent time [*Stackebrandt*, 2003; *Rossetti et al.*, 2006; *Storti et al.*, 2007]. Strike-slip faults are abutted by N-S-striking basin in the Ross Sea along the entire western Ross Sea margin [*Salvini et al.*, 1997; *Hamilton et al.*, 2001; *Storti et al.*, 2001] (Figure 1). Sedimentary record and seismic lines investigations reveal Paleogene–Early Miocene subsidence episodes along most of these basins (i.e., Adare Basin, Victoria Land Basin, and Northern Basin [see *Davey and De Santis*, 2005; *Davey et al.*, 2006]). In the Adare basin stretching leads to continental breakoff accommodating about 170 km of ENE-WSW oceanic spreading from about 43 to 26 Ma [*Cande et al.*, 2000; *Cande and Stock*, 2004]. The uplift and erosional history of the Admiralty Mountains is considered to be mainly Cainozoic [*Lisker*, 2002; *Fitzgerald and Gleadow*, 1988]. Preliminary fission track analysis near Mt. Minto attests for the presence of an Eocene (48 Ma) denudation event [*Redfield*, 1994]. Morphological analysis in the area shows the development of a vigorous fluvial erosion event controlled and adapted to the main tectonic network until at least Eocene-Oligocene boundary [*Baroni et al.*, 2005]. Finally, the presence of subacqueous volcanism, now standing at almost 400 m, shows a substantial post-eruptive (Late Miocene–Pliocene) uplift [*Mortimer et al.*, 2007].

3. Mantle Structure

[8] The structure of the upper mantle beneath Antarctica has been imaged through regional tomographic techniques [*Danesi and Morelli*, 2001; *Ritzwoller et al.*, 2001; *Sieminski et al.*, 2003] and local investigations, mostly from temporary deployments [*Bannister et al.*, 2000, 2003; *Lawrence et al.*, 2006]. Mantle tomography shows some robust features, including a striking, sharp discontinuity between East and West Antarctica (Figure 2a) where the Transantarctic Mountains trace the boundary between the seismically fast East Antarctic craton and the slower West Antarctic mantle (Figure 2).

[9] Figure 2c shows the v_{sv} per cent variations with respect to anisotropic PREM along a horizontal section at 140 km depth extract from the DM01 model of *Danesi and Morelli* [2001]. The high-velocity continental lithosphere of East Antarctica extends smoothly out of the passive margin of the continent, whereas it terminates in a steep border toward the West Antarctic Rift. The mid-ocean ridge system around the continent shows up in low seismic velocities, particularly marked beneath the Tasman–South Pacific Ridge from where a slow anomaly propagates toward the Ross Embayment and Victoria Land and extends beneath the continent. While deep, saturated slow regions in the upper 250 km are imaged beneath both the Pacific–Antarcntarctic Ridge and in the Ross Sea Embayment (Figure 2c, sections I and III, respectively), the North Victoria Land area would lay over a warm but shallower thermal anomaly (Figure 2c, section II). The transition between slow and fast seismic velocities is imaged 200–300 km inland from the coast in the North Victoria Land and closer to the coast in South Victoria Land, running beneath the entire length of the TAM profile (Figure 2b).

4. Brittle Architecture of the Admiralty Mountains Region

[10] From satellite images, the Admiralty Mountains region shows an Alpine type morphology. Here, the lack of a summit plateau (as observed southward of the Lanterman Fault) indicates a relatively high denudation rate when compared to the surrounding regions. The valley systems show well sculpted U-shaped profile, with truncated spurs, confluent hanging valleys. Crests and valleys show a NW-SE and NE-SW rectilinear tracts cross –cut each other with sharp angles, typical of a structurally controlled morphology (Figure 3a). Morphometric analysis and quantitative geomorphic parameters, in fact, reveals that the valley network can be ascribed to a fluvial origin adapted and controlled by the recent tectonic frame of the area [*Baroni et al.*, 2005]. In

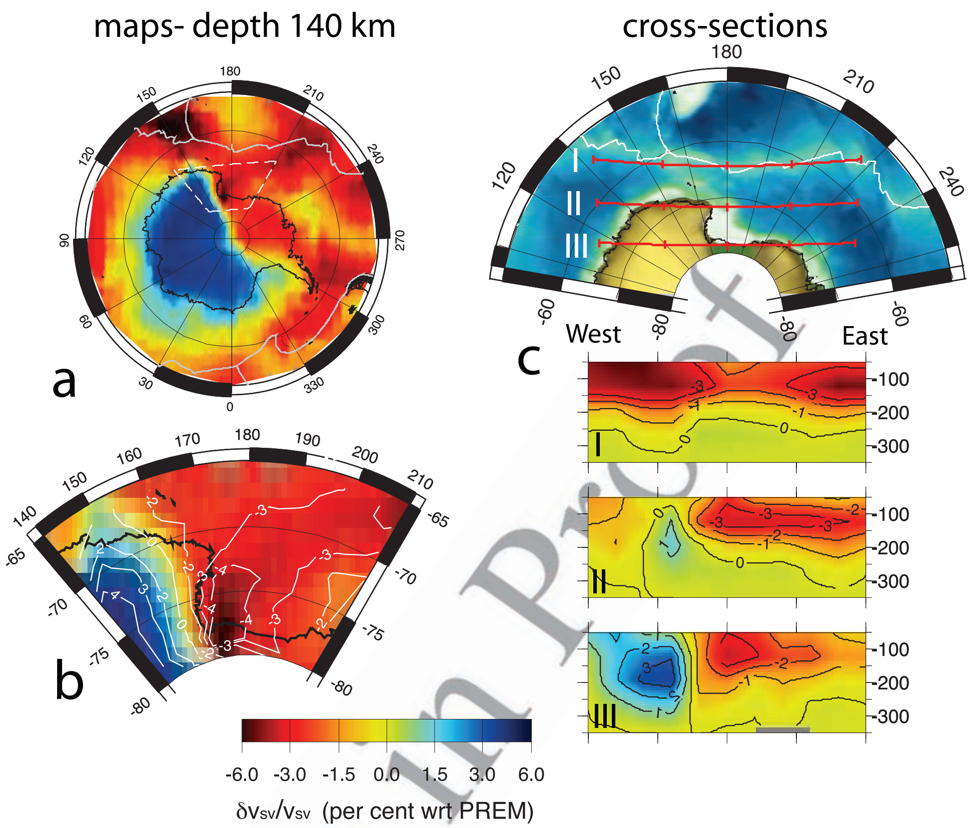
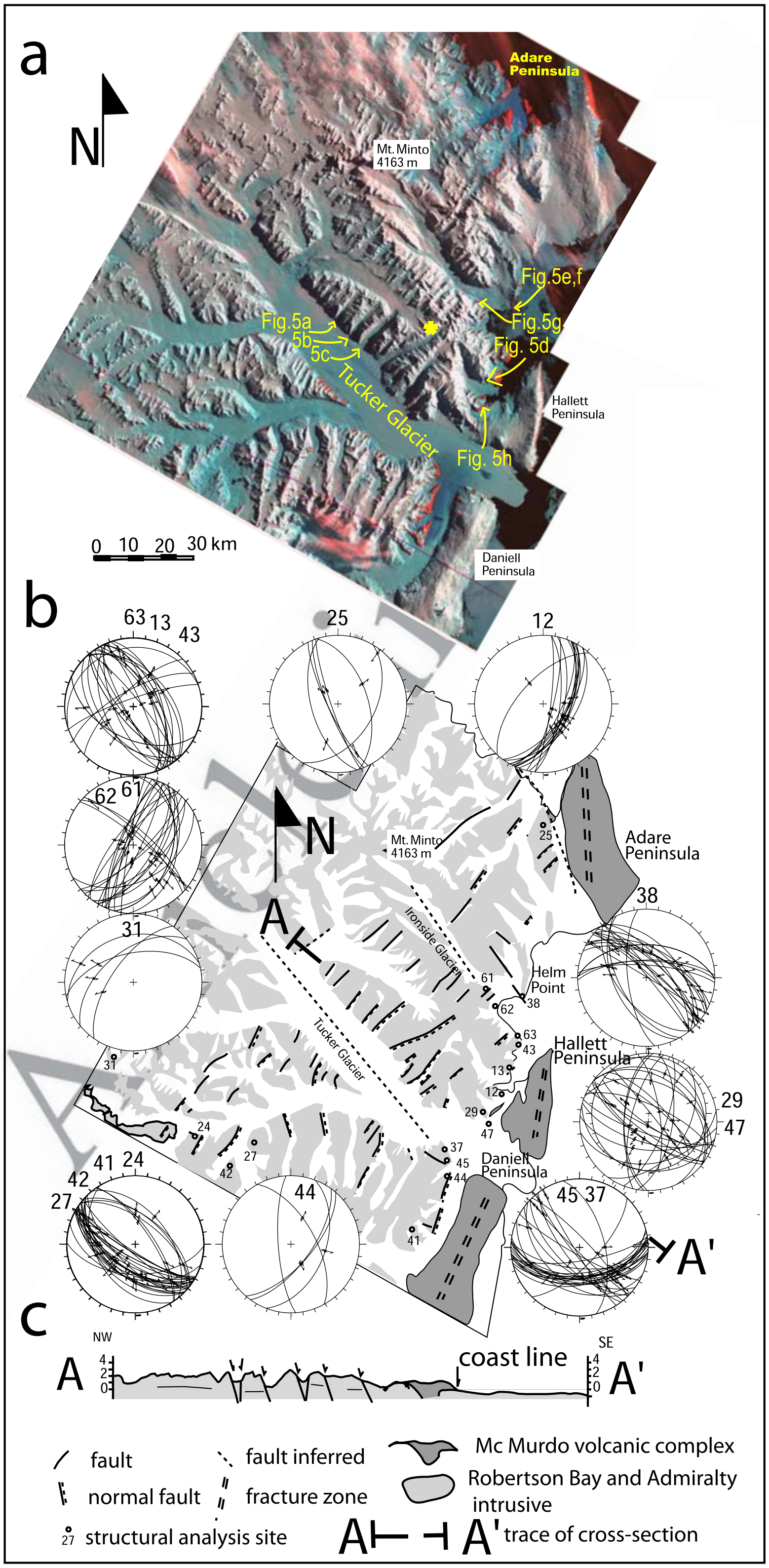


Figure 2. Maps of the shear wave velocity variations in DM01 model [*Danesi and Morelli*, 2001] at 140km depth beneath (a) entire Antarctica and (b) beneath Northern Victoria Land (dashed white line in Figure 2a). Color scale represents percent variations with respect to anisotropic PREM (Saturated blue regions beneath the East Antarctica shield are about 6% faster then PREM). (c) Cross sections show the velocity distribution down to 350 km depth (see location on the top map). Section I crosses the Tasman-South Pacific Ridge, close to the triple junction (note saturated red areas correspond to v_{sv} 5–6% slower then predicted by PREM). Section II crosses the North Victoria Land (study area) close to the craton edge. Section III crosses the sharp discontinuity between the East Antarctica shield and the Ross Sea Embayment. Note warm (slow) anomalies beneath Ross Sea and ocean ridges, and cold (fast) lithospheric roots underneath the Archean shield of East Antarctica.

details, the relationships between these two morphotectonic directions, NW-SE and NE-SW, is particularly evident on the northeastern side of the Tucker Glacier (Figure 3a). The NE-SW valleys and mountain crests are much better expressed than the NW-SE ones; the NE-SW valleys are steeper, narrower, with planar flanks and are shorter in length. In many cases the southeastward dipping valley flanks are steeper and better expressed than the northwestern ones. The NE-SW features intersect at high angle the NW-SE striking valleys that generally show larger and longer glacial valley profiles.

[11] Field work was aimed to define the brittle structural architecture of the region. Flying over the region, we map out the main morphological evidence of faulting (Figure 3a). In 17 sites we found accessible condition to land and to directly collect structural data (Figure 3b). In these sites we analyze the fracture and the fault system, measuring their orientations and defining their kinematics. Fault-kinematic analysis has been carried out using classical structural criteria (grooves, slickensides, Riedel shears, shear bands, offset of geological marker etc.) to deduce sense of slip in brittle fault zones [e.g., *Petit*, 1987]. More than 120 faults with kinematic indicators were collected. Structural observations documented that the two, nearly orthogonal morphologic lineaments indeed correspond to two distinct populations of faults (Figure 4). The first fault set strikes NW-SE or WNW-ESE and consists of hundreds to thousands of meters length scale fault strands. This fault population is rather well expressed over the whole area, but particularly dense along the margins of the two NW-SE main glacial valleys of the Tucker Glacier (sites 45, 37 and 47; Figure 3b) and of the Ironside Glacier (sites 63, 13,43, 38; Figure 3b). It shows dominantly normal dip- to oblique-slip dextral kinematics (Figure 4a). Occasionally, reverse faults are also observed. Offsets of geological markers along the fault generally spans from centimeters to several meters. In several sites, minor faults reactivated the pre-existing steeply dipping foliation of the Robertson Bay Group rocks.


a
N
Adare Peninsula
Mt. Minto 4163 m
Fig.5e,f
Fig.5g
Fig.5a
5b
5c
Fig. 5d
Tucker Glacier
Hallett Peninsula
Fig. 5h
0 10 20 30 km
Daniell Peninsula
b
63 13 43
25
12
62 61
31
38
29
47
41 24
42
27
44
45 37
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Mt. Minto 4163 m
Adare Peninsula
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Tucker Glacier
Helm Point
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A
A'
c
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coast line
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Mc Murdo volcanic complex
Robertson Bay and Admiralty intrusive
trace of cross-section

Figure 3

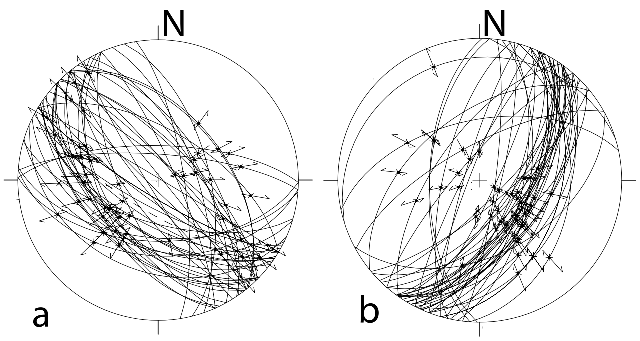

Figure 4. Stereonets (Schmidt net lower hemisphere) showing the trace of fault planes and kinematic indicators related to the (a) first and (b) second episode of brittle deformation.

At site 63 (Figure 5g), NNW-SSE striking normal and oblique faults are arranged in a domino-like structure and conjugate system are titled toward the East. Small McMurdo scoria cones or dykes often occur within the damage zones associated with this fault set. This is particularly evident at sites 24, 25 and 41, where it is possible to observe that scoria cones are positioned on top or nearby the main fault zones (Figure 3b). The relationship between volcanism and faulting is also observed at site 38 (Figure 3b), where the main fault zone of the Ironside glacier is visible. The fault zone itself is constituted by a steeply dipping, dense and regularly spaced (about 2–4 m) faults, overall arranged with a negative flower geometry. There, fault kinematics is oblique- to dextral WNW-ESE strike-slip and conjugated NNW oblique-sinistral fault. Superimposed set of slickenside shows strike-slip motion overprinted by dip-slip one. The fault surfaces are decorated by epidote segregation, indicating that fault motion was accompanied by discharge of epithermal fluids (Figure 5e). The fault zone itself are intruded by a swarm of subvertical N-S bearing, 1–2 m thick and 10- to 20-m-long McMurdo dykes. The location and the orientation of the dykes attest that NW-SE oblique dextral fault zone act as preferential pathway for the rise up of magmatic fluid during an overall E-W extensional regime. Fault activity is also active after the dyke emplacement as dykes are crosscut by a 1–2 m regularly space system of small NW-SE fault and fracture (Figure 5f). This demonstrates that McMurdo dykes swarm emplaced inside NW-SE fault zone during its continuous motion.

[12] The second fault system strikes NE-SW to NNE-SSW, roughly parallel to the coastline, progressively turning to a more northerly strike toward the Daniell Peninsula (Figure 3). The geomorphological expression of this fault system is typified by kilometer-scale fresh fault scarps (Figures 5a, 5b, 5c, and 3a), distributed over a 60–80 km wide area, down stepping from the higher peaks (e.g., Mt. Minto, Figures 1 and 3c) toward the coast. South of the Tucker glacier, their trace becomes elusive, and possibly continues offshore (Figure 1). On the northern flank of the Tucker Glacier valley, the fault system is constituted of 60°–70° dipping, westward plunging fault scarps (Figure 5d) with about 5 km of average separation. Inclination of the fault system gets shallower to about 50° moving toward the coastline, and defining an overall domino block faulting (Figure 3c). Main southeastward dipping fault planes are often accompanied by antithetic faults forming narrow and V-shaped steep valleys. At various sites (e.g., sites 12 and 62, Figure 3b) faults are arranged to form a domino array and conjugate system locally tilted toward NE (site 62, Figure 5d). Slickensides and grooves on fault planes indicate systematically a normal dip-slip motion, accommodating a general NW-SE/WNW-ESE trending maximum extension direction (Figure 4b). Normal faults crosscut and rework strike-slip faults belonging to the previous tectonic episode. At several sites (e.g., site 62, 61, 63), slickenside overprinting relationships on faults surfaces indicate dip-slip reworking on early oblique and strike-slip kinematics. At site 63, along the flank of the Ironside glacier, N30°E, 70°NE dipping fault crosscut the previous NW-SE faults (Figure 5g). This local structural observations, showing that this second fault system crosscut and reworked the first one, are clearly confirmed by morphological observations as the NE-SW linear valleys and crests are the younger morphotectonic features as over the whole area, crosscutting at high angle the NW-SW ones. In one case, a WNW trending glacier tributary of the Tucker Glacier flows toward the WNW for about 30 km, hence upstream with respect to other glaciers, before turning SW to join the Tucker glacier (asterisk in Figure 3a). As discussed below, the anomalous flow of this glacier could be controlled by the footwall uplift along one of this fault strands. Importantly, at site 12, faults crosscut and displaced McMurdo dykes by about 15 m southeastward (Figure 5h). The definition of the amount of extension related to this second tectonic can be done restoring the morphological steps on each fault along the cross section AA′ (Figure 3c). This gives an upper bound on the order of 4–5 km that that could be representative of the total amount of extension.

5. Discussion

5.1. Tectonic Synthesis

[13] Our investigations documents that the brittle structural architecture of the Admiralty Mountains area is con-

Figure 3. (a) Satellite image and (b) corresponding structural map of the Admiralty Mountains. The structural grain shows two sets of faults oriented perpendicular each other. The glacial and maybe older fluvial erosional network is guided and reworked by the fault activity. Yellow asterisk marks the presence of upstream directed glacial valley (see section 5). Structural map show the corresponding stereonets (Schmidt net lower hemisphere) where the trace of fault planes and kinematic indicators are shown. Number near stereonets refers to the structural sites indicated in the map. (c) Cross section AA′ illustrates the architecture of the normal fault system.

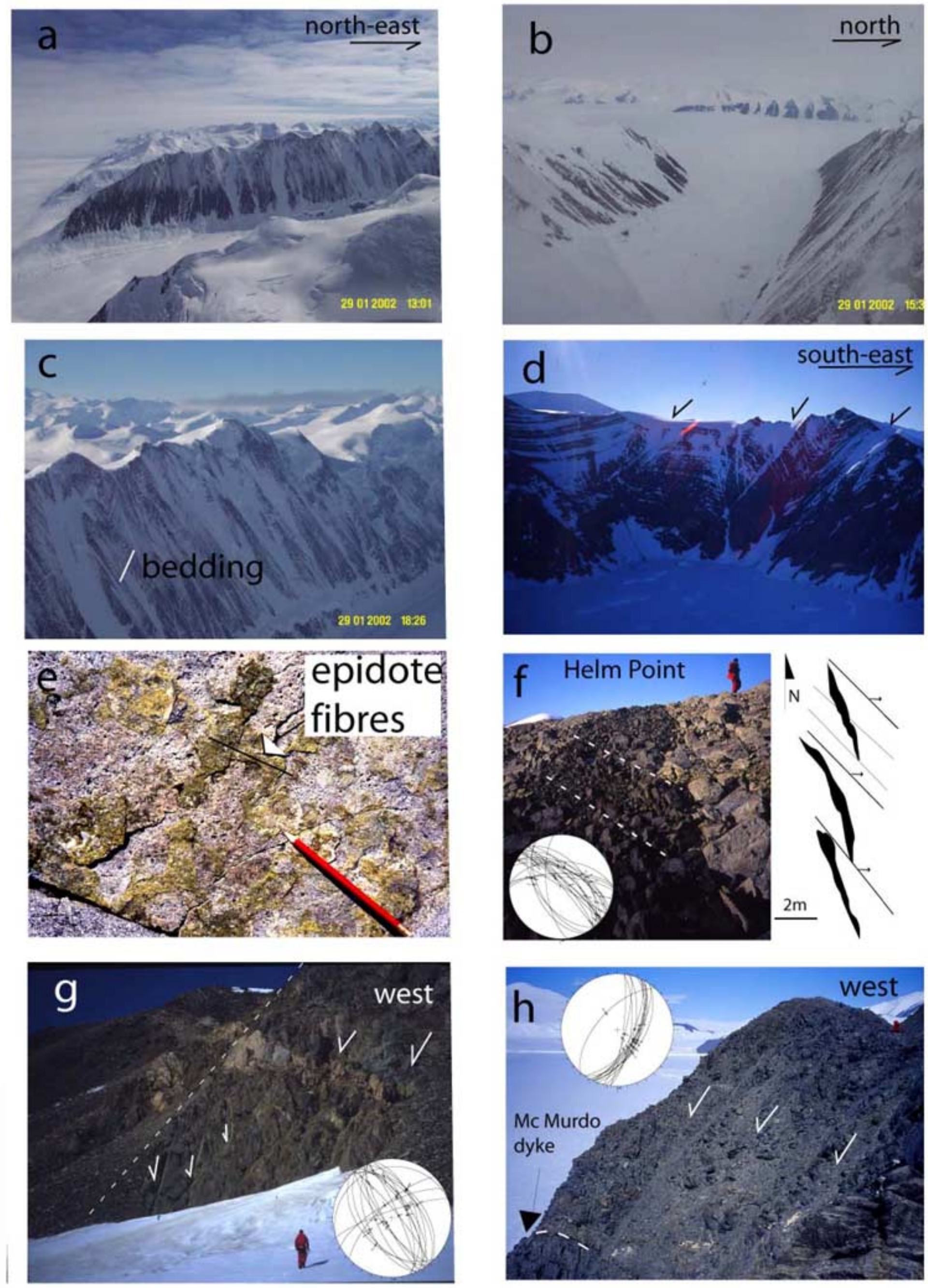

Figure 5. (a–c) Aerial view of the alpine-type morphology of the Admiralty Mountains north of the Tucker glacier. Glacial system developed over a fluvial network controlled by fault zones (location in Figure 3a). (d) System of NE-SW normal faults developed during the second episode of faulting (location in Figure 3a). (e) Detail of oblique-slip fault plane at Helm Point (Figure 3, site 38), showing epidote fibers related to hydrothermal circulation during faulting. (f) View of the crosscutting relationships between faulting and McMurdo volcanic dykes at site 38 (Helm Point) and related field sketch (arrow on fault indicate sense of slip) with corresponding stereonet. Dykes are disposed en echelon, and are subvertical and N-S oriented. (g) System of normal to oblique-slip faults at site 63 (see Figure 3a) related to the first faulting episode, later crosscut by NW-SE normal faults (dashed line). (h) Recent normal fault crosscutting a McMurdo dyke at site 12 and related stereonet (Figure 3b).

trolled by two nearly orthogonal fault systems, NW-SE striking dextral and NE-SW striking extensional, respectively. Our analysis in the field document that the NE-SW system systematically overprint the NW-SE one. This is evident both from the geomorphological and structural analysis. This rules out interpretations arguing for a possible kinematic linkage between the two fault systems, i.e., the NW-SE strike-slip faults as transfer of the NNE-SSW extensional ones (Figure 4).

[14] The age of these fault systems can be constrained by their intimate and mutual overprinting relationships with the McMurdo volcanic products in the study area. In particular, spatial and geometrical relationships between faulting and volcanism suggest that fault-damage zones and fractures represent a preferential pathway for magma ascent. This is documented by the fact that most of the McMurdo scoria cones are located at the intersections between the two fault strands [see also *Läufer et al.*, 2006] (Figure 3) and that dykes developed inside fault zone. Therefore, on the basis of the age of the Hallett Volcanic Province in the region [*Läufer et al.*, 2006; *Mortimer et al.*, 2007, and references therein], the fault systems documented in this study were likely active from Middle–Late Miocene onward. In these terms, this study provide a further argument in favor of a genetic link between brittle faulting and the alkaline McMurdo volcanism in Victoria Land during the Cenozoic [*Salvini et al.*, 1997; *Rocchi et al.*, 2003; *Stackebrandt*, 2003].

[15] Structural data thus document that in a relatively short time span, during and after McMurdo volcanism (last 14 Ma [*Läufer et al.*, 2006]), two major faulting episodes took place in the Admiralty Mountains area. The older, NW-SE striking fault system developed under an overall transtensional regime that is compatible with the regional Cenozoic tectonic of northern Victoria Land [*Wilson*, 1995; *Salvini et al.*, 1997; *Hamilton et al.*, 2001; *Rossetti et al.*, 2003, 2006; *Stackebrandt*, 2003; *Storti et al.*, 2007]. The direction of extension of this faulting episode (N60°–70°E) is also in agreement with the one that could be inferred from the Neogene N20°W striking faulting episode described just offshore of the investigated area, in the Adare Trough [*Müller et al.*, 2005] (Figure 1). Peculiar characteristic of the investigated area is the presence of a younger extensional fault system superimposed on the previous one. It generally strikes NE-SW but tends to gradually turn southward toward a more NNE strike. The area affected by faulting is confined to 30–40 km inland and becomes more evident toward the coast, where the large shield volcanoes occur. The landscape of the area is clearly controlled by this recent faulting event. Geomorphological analysis documented that the regularly spaced NE-SW trending Alpine-type narrow glacial valleys evolved over an older network of fluvial valleys adapted and controlled by recent faulting [*Stackebrandt*, 2003; *Baroni et al.*, 2005]. In addition, the presence of subaqueous volcanic facies now standing at more than 400 m elevation on the Adare Peninsula attests for an important post–Late Miocene uplift [*Mortimer et al.*, 2007]. Cosmogenic dating in neighbor areas of north Victoria Land indeed shows episodes of downcutting valley as young as 6–1 Ma, indicating recent uplift and erosion [*Van der Wateren et al.*, 1999].

[16] All these independent lines of evidences indicate that uplift occurred during continuous faulting. The tectonic controls on landscape are also reflected by the presence of an upstream-directed glacier (asterisk on Figure 3a). The origin of this topographic gradient is in fact probably related to NW-ward block tilting on the footwall block along a major NNE-SSW fault strand. This suggests that at least part of the Alpine-shape morphology and uplift of the Admiralty Mountains has been acquired during these recent episodes of extensional block faulting and subsequent erosion. Furthermore, the large shield volcanoes of the Cape Hallett and Daniell Peninsula are NNE-SSW elongated, thus striking parallel to the nearby fault system (sites 44, 12, 61, 62), and their seaward side is possibly truncated and crosscut by N20°E faults (Figure 3b). Hence, the younger (post-Miocene) volcanic activity is probably fed by these faults and related fractures systems active during and after the volcanic activity. This interpretation is (1) supported post-eruptive uplift of hundreds of meters in the Robertson Bay-Adare Peninsula region [*Mortimer et al.*, 2007], and (2) consistent with evidence for recent deformation just south [*Stackebrandt*, 2003] and offshore of the area [*Müller et al.*, 2005; *Rossetti et al.*, 2006; *Storti et al.*, 2007]. Given the intimate relationships between uplift, faulting, volcanism, we speculate that the transition between strike-slip to dip-slip regime could have been influenced by the increase in the gravitational potential energy during uplift.

[17] On the basis of the above, it is possible to define two main tectonic pulses as responsible for the late Cenozoic tectonic history of the area (Figure 6). The first one initiated at around ~40 Ma. At that time, a major tectonic reorganization occurred, with the onset of strike-slip deformation onshore [*Rossetti et al.*, 2006; *Storti et al.*, 2007], oceanic spreading offshore [*Cande et al.*, 2000] and the contemporaneous onset of magmatism [*Rocchi et al.*, 2002]. This accompanied a major phase of the TAM denudation [*Fitzgerald*, 2003; *Lisker*, 2002], possibly related to fluvial erosion [*Baroni et al.*, 2005] (Figure 6a). This tectonic setting evolved in time, during the onset of NVL glacial system up to the last phase (Late Miocene–Pleistocene), when a renewed surge of tectonics and magmatism produced uplift, faulting and valley downcutting during the development of large shield volcanoes (stage 2, Figure 6b).

5.2. Mantle Upwelling: A Possible Engine

[18] The Admiralty Mountains in Northern Victoria Land is a peculiar region with respect to its surrounding, as it shows an unusual high elevation, it is highly eroded with an Alpine –type morphology area, it shows a large volcanic field (100-km-long shield volcanoes) and finally it shows trace of recent faulting. On this ground, it is then tempting to relate the development of the late-stage NE-SW striking extensional system, peculiar to this region, to an increase in the topographic gradient, contemporaneous with renewed magmatism. A simple scenario that could match all these ingredients is based on the idea that of mantle upwelling from a hotter region adjacent to the possibly colder, but

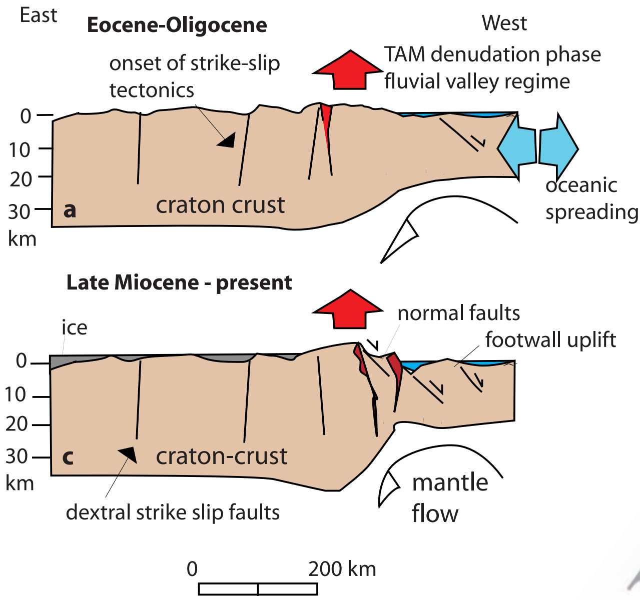

Figure 6. Two stages cartoon for the evolution of the Admiralty Mountains and surrounding area to illustrate the relationships between faulting, uplift and magmatism. (a) The first stage emphasizes the onset and climax of deformation in the late Eocene–Oligocene, whereas (b) the second stage is to illustrate the recent (from late Miocene onward) surge of deformation and magmatism. Crustal section in Figure 6b is from *Lawrence et al.* [2006].

likely stiffer cratonic one (schematized in the Figure 6 cartoon). This could have produced crustal bulging, extensional collapse and final magmatism. In other words, thermal anomalies could have produced enough topographic relief during the late Neogene to increase the gravitational potential energy (GPE) differences significantly, to the point where the induced tractions were able to overcome the strength of the upper crustal layer. This surface rupture can be facilitated if normal faults are rooted into preexisting, surficial crustal decollément inherited from the Paleozoic orogenic phases. This process could be accelerated or even triggered by localized unloading due to deglaciation that could have also favored postglacial uplift further increasing the GPE gradient [*Stackebrandt*, 2003].

[19] The scenario proposed here independently supported by seismic tomography images showing that Ross Sea is indeed positioned on top of a vertical low-velocity structure extending from the asthenosphere (Figure 2) down to the transition zone [*Sieminski et al.*, 2003]. While the resolution of the tomographic model inhibits local-scale considerations, it is noteworthy that the faulted zone of the Admiralty Mountains is indeed unique along the Northern Victoria Land, being located on top of low-velocity anomaly of −2%. This anomaly extended over the Ross Sea anomaly is a part of a NW-SE striking belt of low-velocity zones rooted in the Balleny Islands and in Mary Bird Land, and, although less pronounced [*Sieminski et al.*, 2003], it is juxtaposed to the East Antarctica craton's thick (150–250 km) high-velocity anomaly [*Morelli and Danesi*, 2004] (Figure 2a). The geochemical characteristics of the McMurdo magmatism confirm that the origin of magma can be related to a deep thermal anomaly. In particular, just south of the studied area, geochemical an isotope analyses show that an early EM source, possibly resident in the continental lithosphere mantle, is progressively replaced by a HIMU type source that might be related to a mantle plume [*Rocholl et al.*, 1995]. This signature is typical of areas subjected to extension where the lithosphere component is diminished during progressive stretching and thinning under the action of continuous upwelling [*Rocholl et al.*, 1995].

5.3. Mantle Traction From Global Flow: Testing the Engine

[20] Several models have been proposed to explain the tectonic evolution of the region, and in particular the uplift of the TAM. *van der Beek et al.* [1994] proposed a mechanical necking of an elastic plate model and *ten Brink et al.* [1997] and *Lawrence et al.* [2006] modeled flexure due to the effect of conductive heating of a mantle buoyant thermal load. Seismic transects from the young WARS lithosphere to the old thick east Antarctica craton can then be used with a flexural model to fit the free-air gravity anomaly, accounting for TAM by means of a thin (<5 km) and flat crust [*Lawrence et al.*, 2006]. An Eocene mantle thermal anomaly embedded in a large-scale upwelling [*Finn et al.*, 2005] has also been proposed as a driving mechanism to explain the origin of the Adare spreading ridge between East and West Antarctica and its large crustal thickness anomaly [*Müller et al.*, 2005]. The scenario proposed in the cartoon in Figure 6 belongs to this class of thermal models. To test the possible link between thermal upwelling and tectonic features, we computed mantle flow underneath Antarctica using a *Hager and O'Connell* [1981] type of flow model. In this way we can image if the present-day distribution mantle anomaly is able to produce a mantle upwelling in the investigated area.

[21] Figure 7 illustrates the reference model results showing sublithospheric tractions exerted by mantle flow (assumptions and details of the computation are described by *Becker and O'Connell* [2001]). The horizontal components ("horizontal tractions") are shown as vectors, the radial component as coloring, upwelling (red) to downwelling (blue), and amplitudes are on the order 5 and 40 MPa, respectively. The reference model is set up using a purely viscous, incompressible rheology and only radially variable viscosity (the lithosphere of 100 km thickness is 100 times stiffer than the upper mantle which has a viscosity of 1021 Pas). Circulation is driven both by plate-motion induced flow and by mantle density anomalies; the latter are inferred from the global SMEAN composite tomography model [*Becker and Boschi*, 2002]. This large-scale (spherical harmonic degree ~30) model has been shown to lead to a better match than other tomography structures with regard to global geophysical observations [*Steinberger and Calderwood*, 2006], and best fit parameters from our previous work [*Becker et al.*, 2003] were used for our flow computations. The tractions as shown in Figure 7 do not

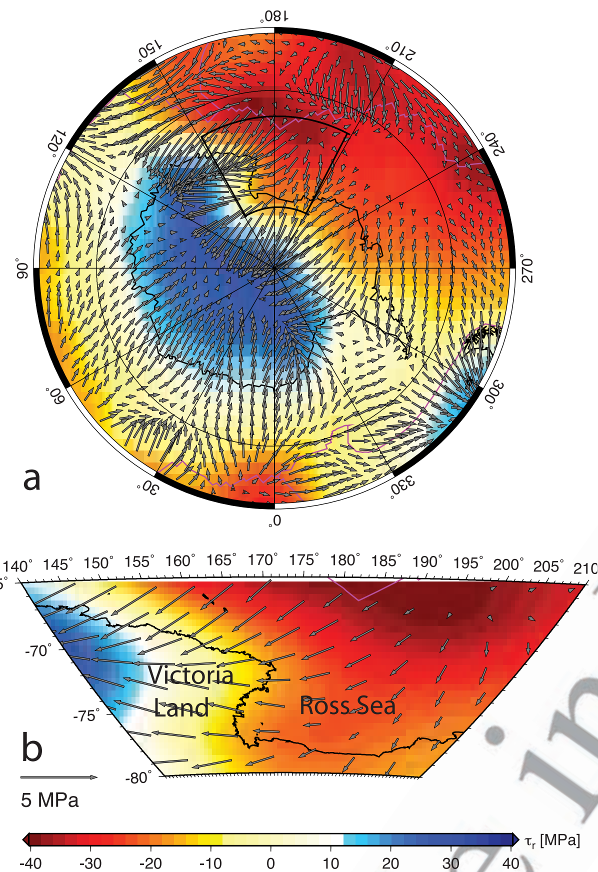

Figure 7. (a) Tractions exerted by mantle drag on the lithosphere at 100 km depth below Antarctica with (b) a zoom on Northern Victoria Land. Horizontal components (“horizontal tractions”) are shown as vectors, and the radial component is shown as coloring, upwelling (red) to downwelling (blue). Mantle flow are inferred from large-scale flow computation that incorporates the effect of plate motions and active upwellings as inferred from SMEAN tomography model [*Becker and O’Connell*, 2001; *Becker and Boschi*, 2002]. Red and blue colors indicate negative (uplift) and positive (depression) radial forces, respectively.

include the effect of GPE variations in the lithosphere [e.g., *Lithgow-Bertelloni and Guynn*, 2004], and we also do not include any smaller-scale structure as may be inferred by from regional models [e.g., *Danesi and Morelli*, 2001] for simplicity.

[22] The result of this large-scale model shows that mantle flow in the Ross Sea area are presently affected by vigorous upwellings whose related tractions would act to uplift the lithosphere (red regions in Figure 7). Comparison with models where tractions are inferred from the shear induced by plate motions alone show that the resulting tractions are very small, implying that shear drag due to plate motions is relatively small, as expected. We also computed tractions for a model where anomalies in the top 220 km of the mantle were excluded, because the cratonic lithosphere may be strongly affected by compositional anomalies. The traction amplitudes for this model are reduced by a factor of ∼2 from those shown in Figure 7, but the patterns are very similar. The amplitude of the tractions was also found to be sensitive to the viscosity structure, but patterns are consistent irrespective to parameter choices (e.g., viscosity profile, tomographic model). Nonetheless, the value reported here are typical for those predicted by global mantle flow estimates [e.g., *Lithgow-Bertelloni and Guynn*, 2004]. Importantly, those values are representative for the deviatoric stress acting within the asthenosphere, loading the plate from underneath. Within the plate on top, stresses can be much higher locally, for example, owing to rheological layering and strength heterogeneity, particularly before the initiation of faulting [e.g., *Burov and Guillou-Frottier*, 2005].

[23] Summing up, the present-day distribution of velocity anomaly inside the mantle predicts an extensional domain in the Ross Sea extending inside the Admiralty Mountain region due to upwelling centered below the ridge just north of the Ross Sea. Of course, this model is not intended to analyze the superimposition between the two deformation events nor the local structure of the studied area. This is mainly because the GPE gradient and hence the crustal contribution is not included. So even if the scale of observation are quite different, and the model itself is conditioned by the resolution of global tomography, the flow model indicates that the pattern of deformation of our field study area may be associated with the ascent of hot mantle material off to the northeast. This flow may provide the explanation for the overall origin of lithospheric deformation, and the continued forcing needed to sustain extension over several Ma. For region surrounded by ridges, such as Antarctica or Africa, local or mantle upwelling are likely the source of intraplate deformation. In particular, the model predicts that the study area should be submitted to an overall E-W (ranging from N70° to N110°) oriented extensional strain field. This extensional strain field is similar to the one observed for the first episode of deformation. It is then possible that the direction of extension of the second, more recent episode could have been influenced by the crustal collapse from the high elevated region. It is however remarkable that also the major strike-slip belt affecting the North Victoria Land [*Salvini et al.*, 1997; *Storti et al.*, 2007] is nicely predicted in the model of Figure 7, being positioned in correspondence of the transition zone between the WARS extensional (red) and compressional cratonic region (blue). This tectonic scenario is plausible as the transition zone between these two rheologically distinct regions should act as a stress guide to propagate deformation [*Salvini et al.*, 1997].

[24] This model does not pretend to investigate on the origin of mantle upwelling neither on its timing: a more time-dependent refined geodynamic modeling needs to be conducted, taking into account regional seismic tomography and lateral viscosity variations. Previous models proposed that a deep plume model could explain the HIMU signature of volcanism and the seismic velocity anomaly. However, the lack of a clear hot spot track and the observation that the low-velocity signature appears to not be rooted in the lower

mantle favors a different hypothesis [cf. *Courtillot et al.*, 2003]. The edge convection model, that is a convective instability circulation along a craton, is an alternative mechanism to induce small-scale convection with upwelling located at distance of 500–800 km from the edge border of a slowly moving craton [*King*, 2007]. *Finn et al.* [2005] suggested a mantle long-lived overturn model driven by an old Late Cretaceous episode of slab break-off to explain the origin of the Late Cenozoic volcanism. Regardless of its origin, an advection model coupled with plate reconstructions shows that the thermal anomaly could be as old as Eocene, and might become more focused over the Neogene [*Müller et al.*, 2005]. This anomaly would then create the necessary condition for the onset of the McMurdo volcanism and the stress necessary for the separation between East and West Antarctica [*Finn et al.*, 2005].

[25] Our data supported by tomographic and computational model suggested that thermal anomaly responsible for older Cenozoic tectonic events, could have been at work even during younger periods (Upper Miocene onward), maybe migrating westward from the Adare basin, in conjunction with and superimposed onto horizontal wrench tectonics [*Salvini et al.*, 1997] related to reactivation of transform faults between Tasmania and Antarctica (Balleny to George V transform faults) [*Storti et al.*, 2007]. The implication of our model is that tectonics in the Ross Sea region is active up recent times and dominated by extension at its northern termination. There, extensional deformation overprints a previous episode of oblique/strike slip tectonics controlled by NW-SE striking fault segments. We consider that a hot, large-scale mantle upwelling flowing toward the cold cratonic root is the most likely cause for the extensional shear stress below the Admiralty Mountains region. Indeed, the episodic reactivation of craton margin related to mantle dynamics has been commonly described also in other regions, such as along the East European craton margin [*Artemieva*, 2007]. The relationships between topography, deformation and magmatism in the northern Victoria Land also suggest that the extensional faulting could be related to the stress field induced by the resulting GPE differences stored inside the crust. Assuming this model is correct, we speculate that part of the elevated topography of the TAM in Admiralty Mountains region was attained recently, in post–Late Miocene times [*Mortimer et al.*, 2007]. If the relationships between tectonics, morphology and volcanisms deduced from our study is correct, we may expect signatures of an even younger event of uplift and erosion, as described offshore [*Müller et al.*, 2005]. Our hypothesis can be tested by means of more detailed fission track and cosmogenic dating, as well as by a more accurate dating of the McMurdo volcanic products. In this way, we could better constrain the relationships between erosion, magmatism and tectonics along the steep cliff of the Admiralty Mountains. Importantly, the observation that extension between East and West Antarctica is still at work in recent time and interacts with dextral wrenching [*Rossetti et al.*, 2006; *Storti et al.*, 2007] may have implication for the global plate-reconstruction circuit [e.g., *Steinberger et al.*, 2004].

6. Conclusion

[26] Our study documents two subsequent episodes of deformation occurring from Middle Miocene onward, concurrently with the McMurdo volcanism in the Admiralty Mountains region. The first is dextral transtensional whereas the second is purely extensional. Our data show that extension in the area pursued until recent times. We suggest that extensional tectonic has been driven by mantle upwelling and associated increases of topographic relief in a "active rifting" fashion. This mechanism may explain the emplacement of large shield alkali volcanoes, and the scenario is supported by analysis of seismic tomography, which shows low-velocity anomalies just below the studied area. We put our model to an initial test by computation of tractions as induced by large-scale mantle flow, documenting that extensional stress in the study region may be related to convective patterns at the boundary between the East Antarctic craton and the hot WARS province. Our hypothesis suggests to reconsider the idea that the area get inactive from the Mid-Miocene and confirms that northern Victoria Land is a key area to unravel modes of active tectonics in Antarctica.

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